A Comparative Study of Kaersutite in the Egersund Dikes and SNC Meteorites

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Abstract

Martian meteorites aka SNC (Shergottite, Nakhla, Chassigny) meteorites, allow scientists the opportunity to study the interior of Mars. Petrologic examinations of Shergottite and Chassigny reveal an uncommon occurrence of the amphibole kaersutite. Kaersutite is usually found to crystallize in undersaturated alkaline basalts. It has been found in tholeiitic rocks in only two localities: melt inclusions in phenocrysts in the SNC meteorites, and in a melt inclusion in an olivine phenocryst in the Ol-tholeiitic Egersund dikes located in SW Norway. This study compares the bulk rock chemistry, kaersutite chemistry, and petrology of the SNC meteorites and the Egersund Ol-tholeiitic dikes. The phenocrysts that contain kaersutite in the Shergottite meteorites and the Egersund dikes display similar characteristics such as zoning, strain, and a skeletal texture, and both are interpreted as xenocrysts. However, SNC meteorites were ejected from Mars via impact events that exerted extreme pressure on the rocks, which complicates the petrologic interpretation. Olivine phenocrysts containing kaersutite in the Chassigny meteorites are not believed to be xenocrysts. Since Chassigny is a cumulate, much less about Chassigny's host magma is known. REE (Rare Earth Elements) enrichment of the SNCs indicate that Mars is less differentiated than Earth, but similar geologic processes may still occur. Zonation of pigeonite, interpreted as two-stage magmatic evolution, and the bi-lithic nature of the Shergottites suggest that Martian magmatic processes are complex.

Acknowledgements

I owe an immense amount of gratitude to my advisor Dr. Michael Barton, for without him I would not have been able to tackle such a project. Thank you to my dad, Erik Hagen, for offering invaluable guidance and support throughout this process, I really could not have pulled it off without you. Thank you to Ricky Bowers and our two cats, Waffle and Harry, for always being there when I needed you. Thanks for staying up late with me and motivating me to keep going. Thank you to my friend, Liz Delfing for lending me your professional editing skills and for being such a wise friend. Thank you to Dr. Carey for guiding me through the daunting thesis writing process. Thank you to The Ohio State University and The School of Earth Sciences. The School of Earth Sciences taught me how to be a scientist and I am grateful to every professor whose classroom I sat in. Thank you to my high school math teacher, Cheryl Hutton, without you I don't know that I would have had the confidence to pursue a career in the STEM field.

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Introduction

As early as 400 BC, early astronomers began observing our neighbor, the planet Mars. They marveled at the fiery-red glow and the unusual movements as they charted the planet's path through our night sky. Eventually, they could predict the movement of Mars with impressive precision and accuracy. Scientists have never stopped looking up, and today we are even closer to understanding our red neighbor. We have satellites orbiting Mars, mechanical roaming laboratories called rovers on the surface of Mars, and even have rocks from Mars with the discovery of SNC (Shergottite, Nakhlite, Chassigny) meteorites. These meteorites allow scientists to examine the petrology of the planet. Since the SNCs were discovered to be of Martian origin, scientists have made much headway in determining what lies below the Martian crust. Of note to many was the presence of a rare hydrous amphibole called kaersutite. Scientists have theorized that the occurrence of this mineral is proof that the Martian mantle is much more hydrous than previously thought. Martian kaersutite is a focus of this study, but for a different reason—its occurrence in Martian SNC meteorites appears to be very similar to one terrestrial occurrence, the olivine tholeiitic Egersund dike. Kaersutite is almost always found to originate in alkaline magmas, however SNC meteorites and the Egersund dikes boast kaersutite that is in tholeiitic basalts (Miller, 1996). Miller's 1996 thesis pointed out that one of the only other occurrences of kaersutite included in an olivine grain in a tholeiitic rock was in the SNC meteorites. Because the mode of kaersutite occurrence and bulk rock chemistry of the Egersund dikes appear to be consistent with that of the Martian meteorites, it was hypothesized that conditions that led to formation of the kaersutite in the Egersund dikes can be used as an analogue for the formation of kaersutite in Martian meteorites. This thesis aims to expand on that hypothesis to compare the geochemistry and the petrology of the olivine tholeiitic Egersund Dikes to that of the SNC meteorites and to compare the chemistry of Martian kaersutite to terrestrial kaersutite.

BACKGROUND

Kaersutite

The mineral Kaersutite is a relatively rare, titanium-rich amphibole (~5–12 wt%). The overwhelming majority of kaersutite is found in ultramafic xenoliths or xenocrysts whose host magma is an alkaline basalt (Barton, oral communication, 2017). Kaersutite is a hydrous mineral and has the standardized chemical formula [$NaCa_2(Mg,Fe^{2+})_4TiSi_6Al_2(O+OH)_{24}$]. Hydrous minerals are important in the broader understanding of the mantle, because they can produce dehydration reactions that can control magma genesis and the quantity of melt produced (Merrill and Wyllie, 1975). Many have used the presence of kaersutite in Martian meteorites to estimate water contents, but these estimates require many assumptions and are not completely reliable (McSween, 1994). Experimental results show that kaersutite can grow with very little water present (Merrill and Wyllie, 1975). Kaersutite is stable at pressures above 1.5kb in the Earth (McSween, 1994), with most studies of terrestrial kaersutite generally concluding that it forms at high pressures corresponding to the lower crust or the mantle. Martian kaersutite generally has a much lower water content than terrestrial kaersutite (McSween, 1994).

Egersund Dike Ol-tholeiite Geology

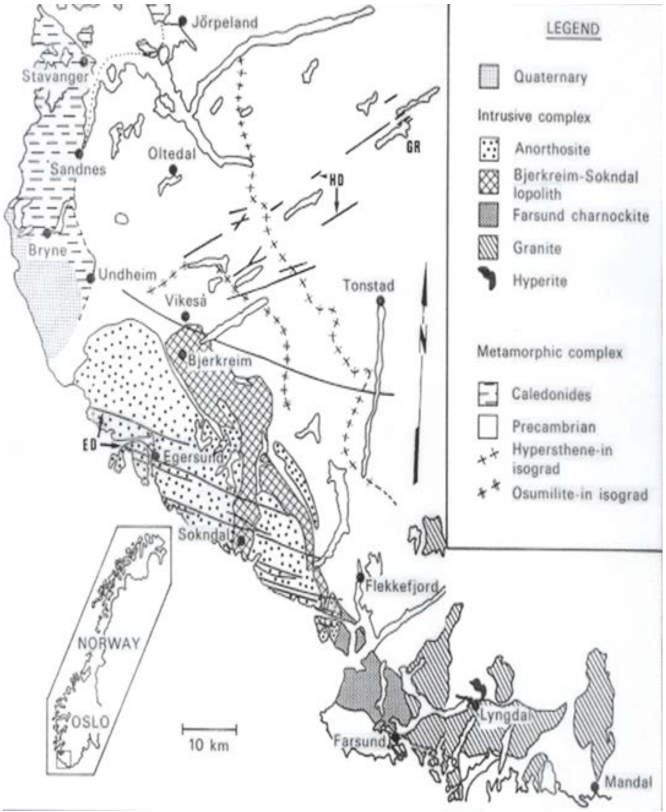


Figure 1 Regional geology of SW Norway (Venhuis and Barton, 1986).

The Egersund dike swarm is located in SW Norway and is made up of olivine tholeiites, tholeiites, and trachybasalts. The Egersund dikes were emplaced along a WNW-ESE trending fault system during the breakup of the supercontinent Rodinia, and are very well preserved showing little evidence of metamorphism (Venhuis and Barton, 1986 source found in Miller, 1996). They are believed to have begun to crystallize at high pressure with an estimate of initial crystallization occurring at of 6–13 kb (Miller, 1996). Age dating of the dikes by Miller (1996) reveals that emplacement occurred at either 649±7 (million years, Ma) or 616±1 Ma during plume-initiated rifting which caused the separation of Baltica and Laurentia, and the formation of the Iapetus and Tornquist Oceans (McCann et al., 2006).

The Egersund dikes follow a tholeiitic enrichment trend. Within the swarm, kaersutite occurs only in the olivine tholeiites. The latter are characterized by an abundance of olivine and plagioclase phenocrysts with a groundmass that consists of olivine, plagioclase, clinopyroxene, magnetite, and ilmenite

(Miller, 1996). Kaersutite occurs in melt inclusions in olivine crystals. Melt inclusions are significant as they can give scientists insight into the magma that produced the first crystals in the rock. Finding kaersutite in a tholeiitic-basalt is highly unusual, with no other terrestrial examples known.

Martian Geology

Petrologic and geochemical analyses of Martian rocks have been performed remotely by Martian rovers and analyses of Martian meteorites. However, the knowledge of Martian geologic processes is in no way complete. Like Earth, Mars is an igneous, differentiated terrestrial body with an iron and nickel core and a silica-rich mantle and crust. Mars gets its distinct fiery color from oxidized, iron-rich minerals in its crust (Nimmo and Tanaka, 2005). However, unlike Earth, there is no thermal or morphologic evidence to suggest that Mars is presently volcanically active. Igneous rocks consist mainly of basalts and ultramafic cumulates. The compositions of the analyzed basalts indicate limited fractional crystallization (McSween, 1994). Tholeiitic and alkaline basalts exist on the Martian surface. Alkaline rocks are generally found in the older, more cratered terrain while tholeiitic rocks are younger which indicates magmatic evolution (McSween, 2015). Geological differences between Earth and Mars do exist. Notably, Martian rock forming processes are distinctly different from Earth due to the lack of plate tectonics. Without plates, there is no crustal recycling and therefore very little metamorphism.

SNC Meteorites

The SNC (Shergotty, Nakhla, Chassigny) group of meteorites are igneous rocks derived from Mars. The clear connection of these rocks to Mars was discovered from analyses of the noble gas concentrations in shock melted-olivine. These noble gas constituents were consistent with the composition of the Martian atmosphere (McSween, 1994). The Shergottites were ejected from Mars approximately 2–3 million years ago and Chassigny and Nakhla were ejected around 10 million years ago, however, their original location on Mars remains unknown (McSween, 2005). Meteorites should not be interpreted as representative of the bulk planet, or even the crust. Young, coherent igneous rocks are more likely to survive impact, and this bias is evident in the Martian meteorite samples that have been recovered on Earth (McSween, 2015). The mineralogy of the SNC’s would classify these meteorites as basalts to mafic cumulates, however, the composition of their parent magma remains unknown (Bridges and Warren, 2006). The Shergottites can be sub-divided into basalts and lherzolites. Kaersutite is found in both basaltic and lherzolitic Shergottites as melt inclusions inside pigeonite, a Ca-rich pyroxene (McSween, 1998). The Chassignite is a cumulate that contains mainly Fe-rich olivine with minor pigeonite, augite, and alkali feldspar (McSween, 1994). In Chassigny, kaersutite occurs as a melt inclusion inside olivine; the mode of occurrence is the same as in the Egersund dikes. The Nakhlas contain olivine and pyroxene, but no kaersutite. They do, however, contain secondary minerals such as carbonates and halite. These secondary minerals formed through aqueous alteration indicating the presence of water on Mars (Needham et al., 2013). The SNC meteorites, together, can help tell the bigger picture of Martian geologic processes.

METHODS

Sample Collection

Olivine tholeiitic basalt samples from the Norwegian Egersund Dikes were collected in 1994 and 1995 by Dr. Michael Barton and Dr. Christopher Miller at exposures near the south-western coast of Norway. In order to ensure the correct rocks were sampled, the geology of the area was studied and the dikes were shown to intrude Precambrian gneisses and anorthosites (Venhuis and Barton, 1986 source found in Miller, 1996). The Egersund Dikes occur along a WNW-ESE trending fault system. Many of the larger exposure have been eroded rendering their exposure poor. Fresh exposures were found in road cuts (Miller, 1996). The rock samples were collected for the purpose of geochemical and petrologic analysis.

Geochemistry

The composition of kaersutite in the olivine tholeiites were determined by electron microprobe analysis done at The Ohio State University using a Cameca SX-50 electron microprobe fitted with four wavelength-dispersive (WD) spectrometers. Egersund dike compositional analysis was completed using a TPD microprobe fitted with a Tracor Northern energy-dispersive (ED) spectrometer. Operating conditions for ED analyses were a with 15 kV accelerating voltage, a 20 nÅ beam current, and a 10 second counting time for each element using a spot size of 1–2 μm (Miller, 1996). Bulk rock compositions of the Egersund dikes were analyzed at the State University of Utrecht using wet chemical methods and at Utrecht and the University of Washington using XRF techniques. Trace element abundances were determined at the University of Washington using ICP-MS techniques. All SNC bulk rock chemistry, SNC kaersutite compositions, and terrestrial kaersutite compositions were compiled during a literature review from peer-reviewed sources. A complete list of raw data and their respective sources can be found in the appendix.

Petrology

Meteorites from Mars are limited to fewer than 50 known samples. Due to the rarity of the meteorites, it was not possible to obtain a sample for petrologic examination. Micrographs and petrologic reports from peer-reviewed sources were used for this study. Micrographs and petrologic information from the Egersund dikes were provided by Dr. Michael Barton at The Ohio State University.

Data Analysis

The major oxide chemistry of the kaersutites in the Egersund dikes were imported into Excel, where the formula units for each element was calculated. All plots were made in the program WinRock. Chondrite meteorite data were used to normalize the REE in the Egersund Dike samples and in the SNC meteorites, because Chondrites are considered to represent the initial condition at the formation of the solar system.

RESULTS

Chassigny Petrology

This meteorite is an achondrite composed primarily of Olivine. The modal composition is approximately 90% olivine, 5% pyroxenes, 2% feldspar, and 1.4% chromite along with other minor components such as melt inclusions (Monkawa et al., 2006) The modal abundance of olivine would classify this meteorite as a dunite.

Olivine: Olivines are euhedral (Figure 2.1) and are not zoned (Monkawa et al., 2006). The forsterite composition of the olivine is reported by Mason et al. (1976) as $Fo_{68\text{-}71}$ which is more iron rich than in many dunites. Planar shock features are evident as radiation cracks and undulatory extinction was observed by Monkawa et al. (2006). Olivine is found to contain rounded melt inclusions containing high-calcium pyroxene and Ca-Ti amphibole (Kaersutite) (Floran et al., 1978).

Pyroxene: Pyroxene is generally un-zoned and has a composition consistent for equilibrium with olivine (Floran et al., 1978). Thin sections analyzed by Harvey and McSween (1994) indicate the major composition of pyroxene to be $Wo_{33}En_{68}Fs_{49}$ classifying the pyroxene as augite. These authors observed calcium-rich pyroxenes poikilitically surrounding Ca-poor pyroxenes.

Chromite: Chromite grains are euhedral and included within olivine grains. This observation lead Floran et al. (1978) to conclude that chromite was first to crystallize from the parent melt. The chemistry of chromites in Chassigny was discussed by Wadwa and Crozaz (1995) who found them to be magnesio-chromite with a magnesium number of 12 to 19.

Plagioclase: Plagioclase is interstitial to olivine grains and was determined by Mason et al. (1976) to have an average composition of $An_{32}Ab_{64}OR_4$.

Melt Inclusion: Round melt inclusions (Figure 2.1–2.3) are found in olivine grains. Floran et al. (1978) determine that these inclusions can be subdivided into multi-crystalline inclusions, monocrystalline inclusions and glass. The multi-crystalline inclusions contain high-calcium pyroxene, pleochroic amphibole and biotite. Further analysis indicated that amphibole was the high calcium-titanium variety, kaersutite. Kaersutite was observed to be 50 to 75 µm in size. Figure 2.2 and 2.3 below show a chilled margin around the melt inclusion inside the Olivine. A melt rich in silica can react with olivine to produce a low-calcium pyroxene.

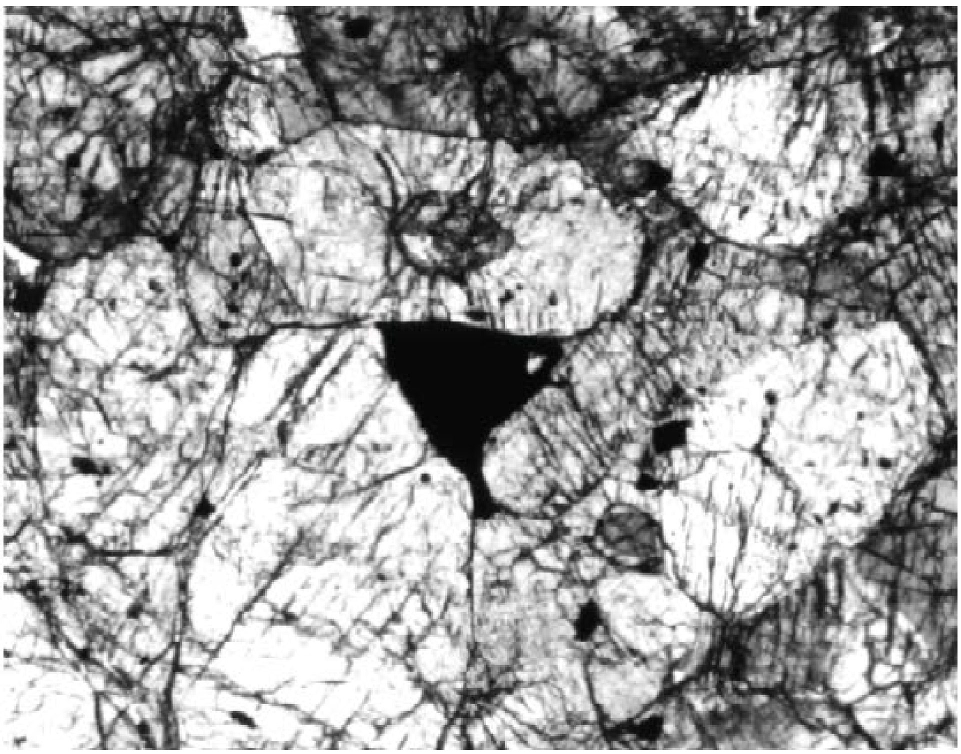


Figure 2.1 field of view is 2.2mm across. Petrographic microscope image in plane polarized light showing chromite and kaersutite containing melt inclusion trapped inside olivine grain. Micrograph source: (Monkawa et al., 2006)

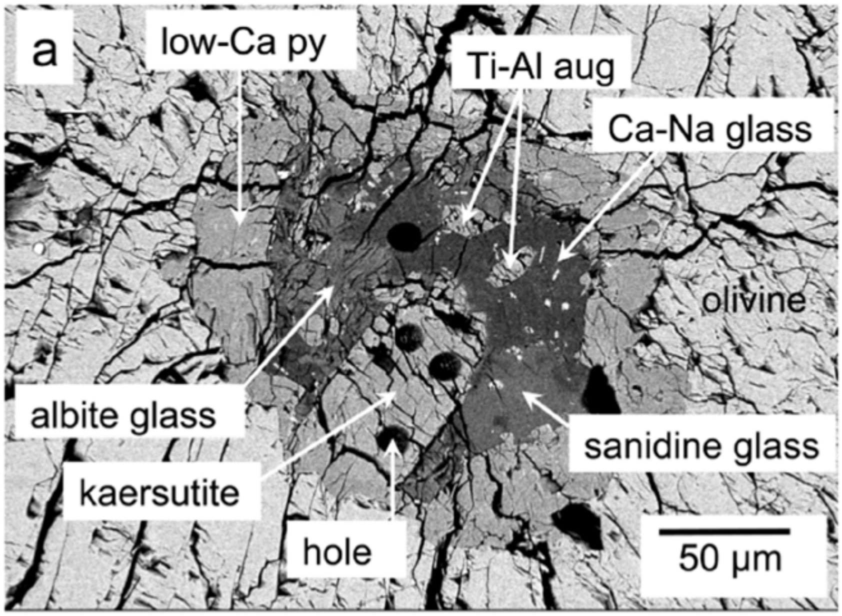


Figure 2.2 Melt inclusions consisting of kaersutite and glass inside olivine grain in Chassigny meteorite. Micrograph source: *Determination of the Fe oxidation state of the Chassigny kaersutite: A microXANES spectroscopic study* (Monkawa et al., 2006)

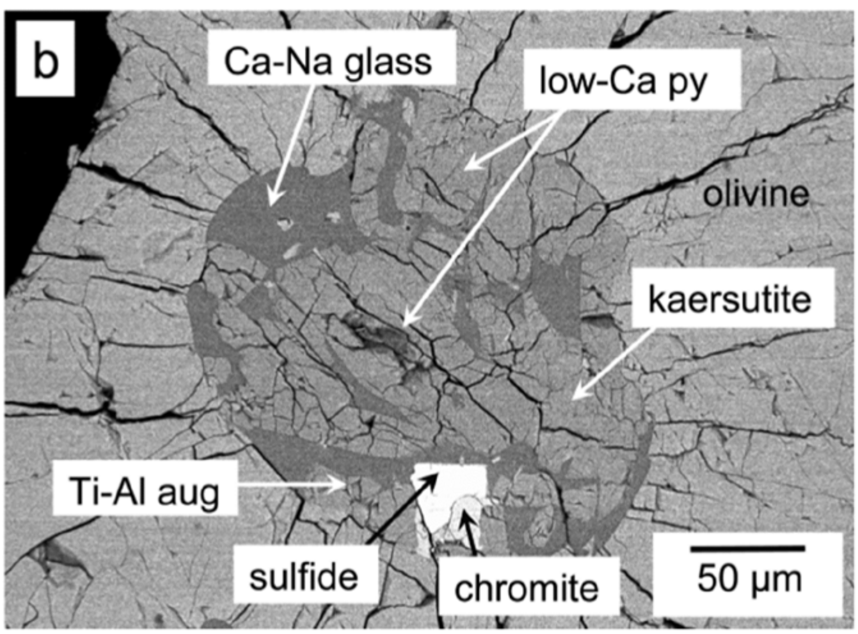


Figure 2.3 close up of melt inclusion in Olivine grain found in Chassigny meteorite. Micrograph source: *Determination of the Fe oxidation state of the Chassigny kaersutite: A microXANES spectroscopic study* (Monkawa et al., 2006)

Shergottite Petrology

Allen Hills lherzolitic Shergottite: This rock was described by Stopler and McSween(1979) as containing two lithologies: poikilitic and non-poikilitic. This thesis focuses on the poikilitic lithology, because that is where kaersutite is found. The poikilitic lithology is characterized by Murakimi and Ikeda (1994) as having megacrysts of chadacrystic olivine and oikocrystic pigeonite, both with abundant magmatic inclusions. This rock also contains minor chromite, plagioclase glass, augite, and pyrrhotite.

Olivine: Olivine is brown and exhibits chadacrystic (xenocrystic) textures. The composition ranges from Fo_{75} to Fo_{70} (excluding quenched olivine that has been shocked). Grains range in size from 0.1 µm–1.0 µm and show corroded outlines (Ikeda, 1998).

Magmatic Inclusions in Chadacrystic Olivine: The inclusions described by Ikeda (1998) have round outlines and are composed of Al-rich, low-Ca pyroxene, fassiatic pyroxene, plagioclase intergrown with Si-rich glass, Si-rich glass, Na-rich rhyodacitic glass, and minor chromite or spinel, phosphates and sulfides. The edges of the inclusions are lined with aluminous pyroxene (Ikeda,1998).

Pigeonite: Pigeonite exhibits oikocrystic texture with abundant magmatic inclusions. These crystals are zoned toward Fe-rich compositions (McSween, 1994).

Magmatic Inclusions in Pigeonite: Inclusions have irregular shapes with diameters between 10µm and 200µm (shown in figures 2.4–2.5). Inclusions are composed primarily of potassium-rich glass with minor kaersutite, spinel, Al-rich pyroxene, Al-poor pyroxene, phosphates, and pyrrhotite (Ikeda, 1998).

Basaltic Shergottite (Shergotty, Zagami, EET7900): These are described by McSween (1994) as being relatively fine grained and containing nearly equal modal proportions of megacrysts of pigeonite ($Fs_{28.7-54.3}$) and augite ($Fs_{19.5-35.0}$). The rocks exhibit a foliated texture due to preferential orientation of pyroxene (Stopler and McSween, 1979). The rocks also contain minor maskelynite veins and pockets. Maskelynite is a glass formed by shock melted plagioclase. There is also minor titanomagnetite, ilmenite, pyrrhotite, whitlockite, and accessory apatite, quartz, baddeleyite, fayalite, and mesostasis (Stopler and McSween, 1979).

Pigeonite: Some pigeonite grains appear skeletal and fractured most likely due to shock (Stopler and McSween, 1979). Pigeonite has a homogenous Mg-rich core, but it's rim strongly zoned toward Fe-rich compositions and maskelynite is also zoned and has sodic composition (McSween, 1994). Twinning and undulatory extinction are common in the clinopyroxenes.

Melt Inclusions: Melt inclusions occur exclusively in the pigeonite cores, and contain kaersutite with spinel and sulfides. Kaersutite is only found in pigeonite grains. (Treiman, 1985).

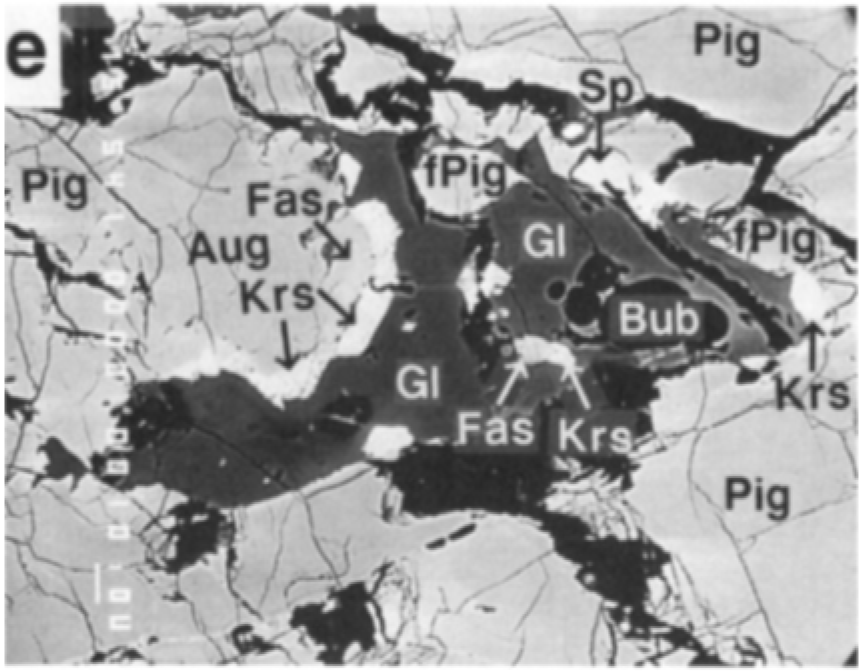


Figure 2.4 Melt inclusion containing kaersutite (Krs), glass (Gl), and bubbles (Bub) inside a pigeonite (Pig) phenocryst. Micrograph source: *Petrology of magmatic silicate inclusions in the Allan Hills 77005 lherzolitic Shergottite* (Ikeda, 1998)

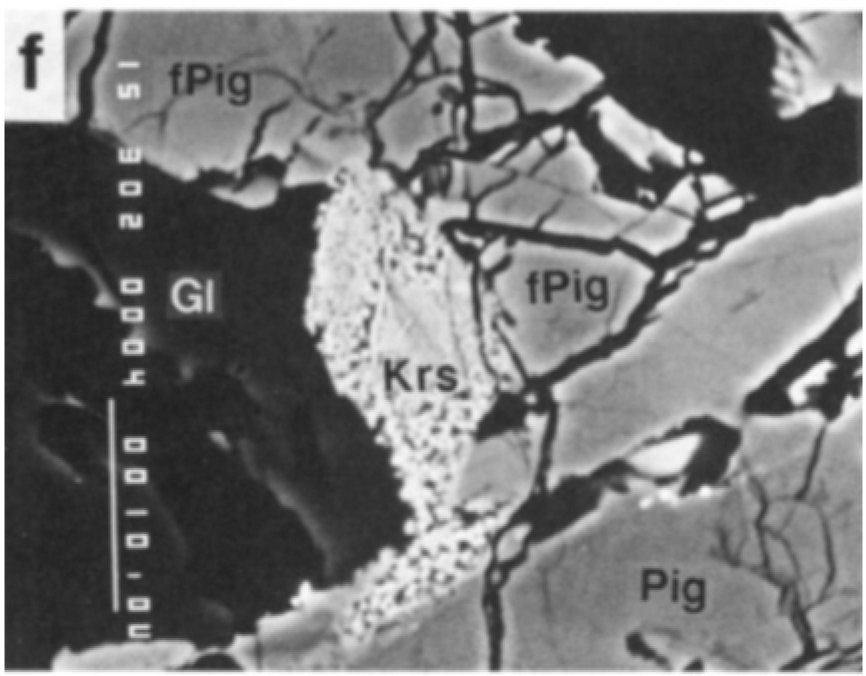


Figure 2.5 Kaersutite (Krs) inside skeletal pigeonite (Pig) phenocryst. Micrograph source: *Petrology of magmatic silicate inclusions in the Allan Hills 77005 lherzolitic Shergottite* (Ikeda, 1998)

Egersund Dike Ol-tholeiite Petrology

The olivine tholeiites are dominated by phenocrysts of olivine and plagioclase set in a groundmass of olivine, plagioclase, titanium-magnetite and ilmenite.

Olivine: The majority of olivine phenocrysts occur as elongate, skeletal crystals (Miller, 1996). The Forsterite composition of olivine reported by Miller (1996) is Fo_{84} – Fo_{76}. Olivines have interesting textural characteristics as described by Ziga and Barton (2005). Some are described as strained, other phenocrysts are intergrown with plagioclase and exhibit a resorbed texture. Some olivine contains inclusions of pyroxene or kaersutite. Olivine phenocrysts containing kaersutite show reverse zoning (cores - Fo_{76}, rims Fo_{82}), which indicates the olivine may be a xenocryst.

Melt Inclusions: The melt inclusions contain high Ca-pyroxene, kaersutite, and rare spinel and apatite (Ziga and Barton, 2005). The inclusions are interpreted to be a partially crystallized melt. The pyroxene is described by Ziga and Barton (2005) as a titanaugite with very high Al_2O_3 and TiO_2 and low SiO_2 and Mg#. The kaersutite crystals appear elongate and skeletal, which is could indicate quenching of the host melt.

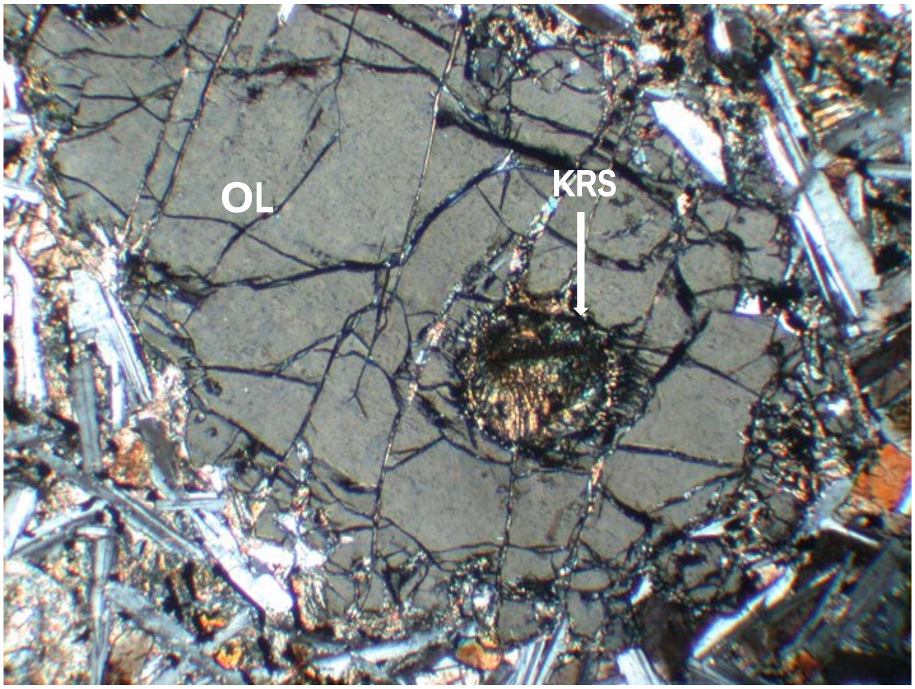


Figure 2.7 Kaersutite (KRS) inclusion in olivine (OL) grain in olivine tholeiitic Egersund dike. Olivine exhibits a skeletal texture. Micrograph provided by Dr. M Barton (Professor Ohio State University)

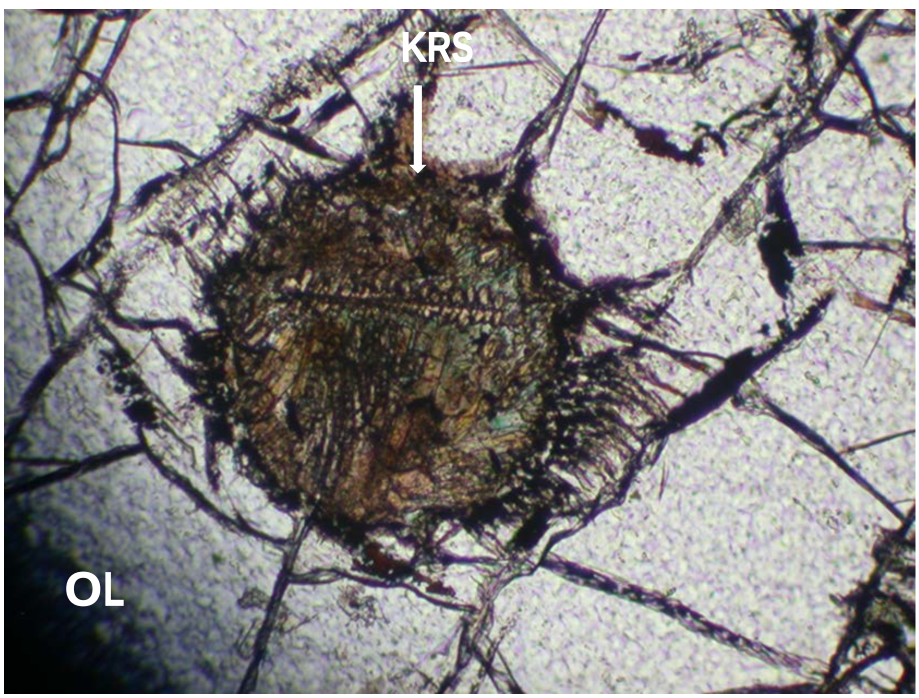


Figure 2.8 kaersutite (KRS) inclusion in olivine (OL) grain in olivine tholeiitic Egersund dike. Skeletal and elongate kaersutite crystals are apparent. Micrograph provided by Dr. M Barton (Professor at Ohio State University, School of Earth Sciences)

Bulk Rock Major Element Chemistry

The Egersund dikes containing kaersutite was classified by Venhuis and Barton (1986) (source found in Miller, 1996) to be olivine tholeiites. Classification of magmatic rocks are made both on mineralogic and chemical composition. As a point of comparison, the major oxide chemistry for both the Egersund olivine tholeiites and Martian meteorites were plotted on Figure 3.1. This figure illustrates the compositional similarities and differences between the olivine tholeiitic dikes and the known Martian meteorite types. Shergottite and Nakhla plot with the egersund olivine tholeiites in the basalt field of composition. Shergottite and Nakhla have SiO_2 content that is similar to that of the Egersund olivine tholeiites. However, the alkali content of the Martian meteorites is much less than that of the Egersund samples. Chassigny does not plot in the same classification field as the Egersund olivine tholeiites or the other Martian rocks. This compositional difference is distinctly related to the mode of occurrence of these meteorites. Shergottite and Chassigny are achonditrites but Chassigny is a cumulate igneous rock and it clearly differs in mode of origin compared to the Shergottites. Shergotty is classified as a basalt whereas Chassigny is an olivine cumulate (i.e. dunite). Chassigny is described by Monkawa (2006) as a dunite with some magmatic inclusions. The bulk-rock silica-oxide and iron-oxide/ magnesium-oxide content of both the olivine tholeiitic Egersund dikes and the SNC meteorites were plotted for comparison in Figure 3.2. Although it was already known that the Egersund rocks that contain kaersutite show an iron or tholeiitic enrichment trend, Figure 3.2 shows that all three Marian rocks also follow a tholeiitic enrichment trend. The mode of occurrence of kaersutite in the olivine tholeiitic Egersund dikes is most similar to the mode of occurrence in the Chassigny meteorite, as they both occur as inclusions in olivine grains. Interestingly, the bulk rock composition and the FeO/MgO ratio of Chassigny show that Chassigny is the Martian sample that is chemically the least like the Egersund olivine tholeiites. Shergotty, a basaltic Shergottite, appears to be compositionally most consistent with the Egersund samples plotted in figure 3.1.

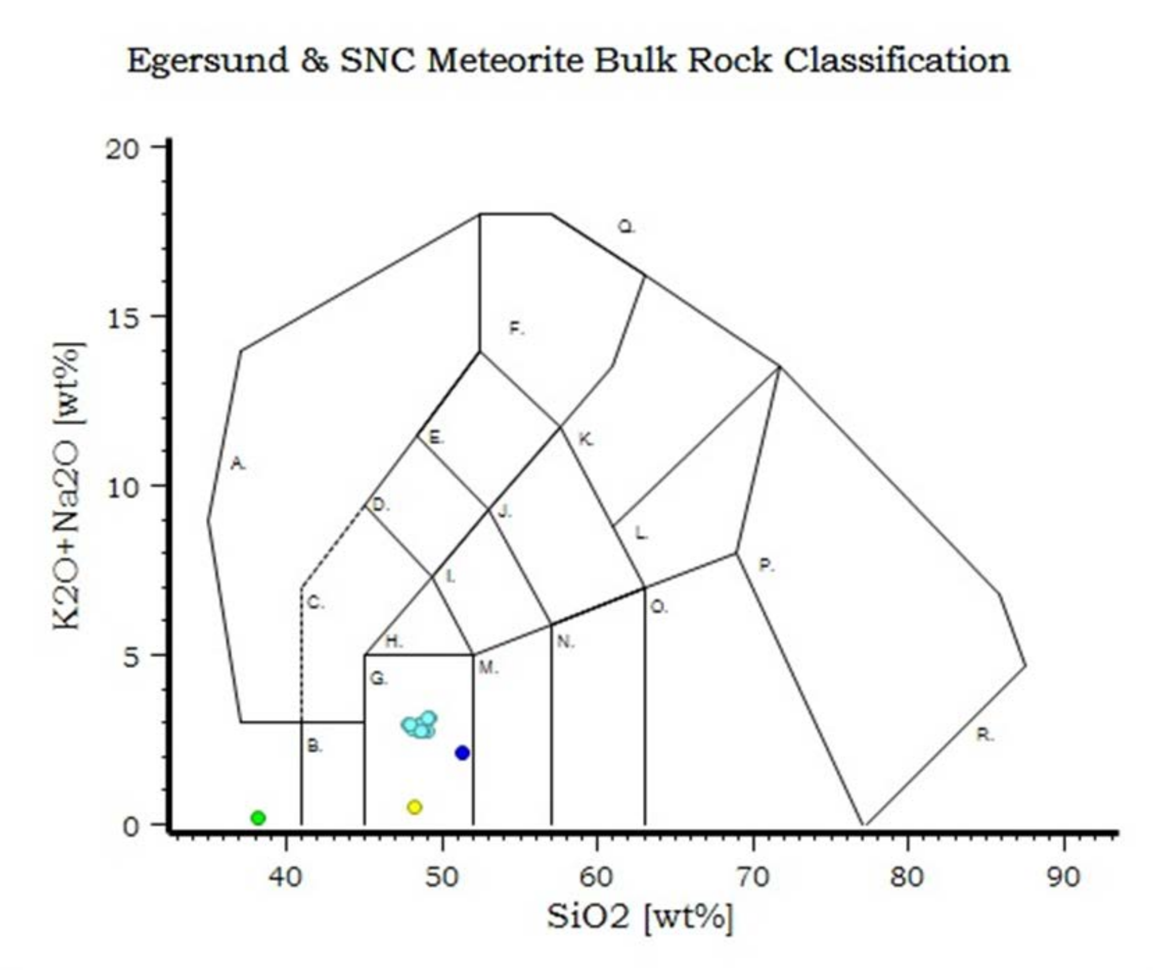


Figure 3.1 TAS plotted according to the Middlemost (1994) classification scheme diagram depicting the bulk rock classification Egersund Ol-tholeiites and SNC meteorites. SNC data sources can be found in the appendix. Plot was made in WinRock. G. = basalt

Symbol Legend

- Egersund Ol-tholeiite
- Shergottite
- Nakhla
- Chassigny

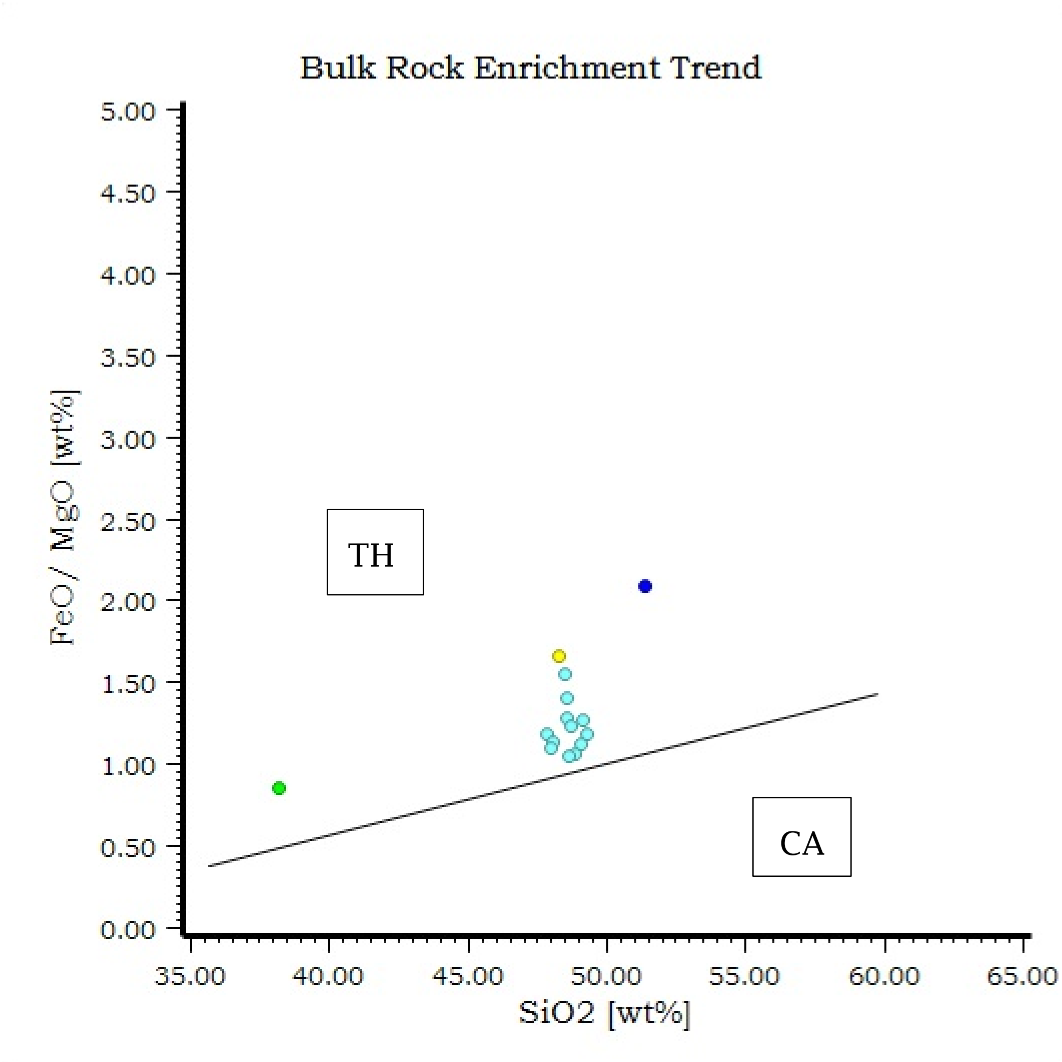
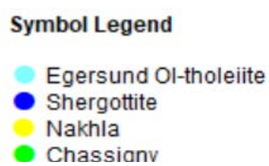


Figure 3.2 Bulk rock major oxide plot showing tholeiitic vs. calc-alkaline enrichment trends. SNC bulk rock data sources are in the appendix. Plot was made in WinRock.



Bulk Average	SiO_2	Na_2O	K_2O
Shergotty [wt%]	51.36	1.29	0.16
Nakhla [wt%]	48.24	0.42	0.10
Chassigny [wt %]	38.16	0.13	0.04
Egersund Ol-tholeiite [wt %]	48.60	2.62	0.66

Figure 3.3 Average weight percent composition of silica and alkalis.

Rare Earth Element (REE) Comparison

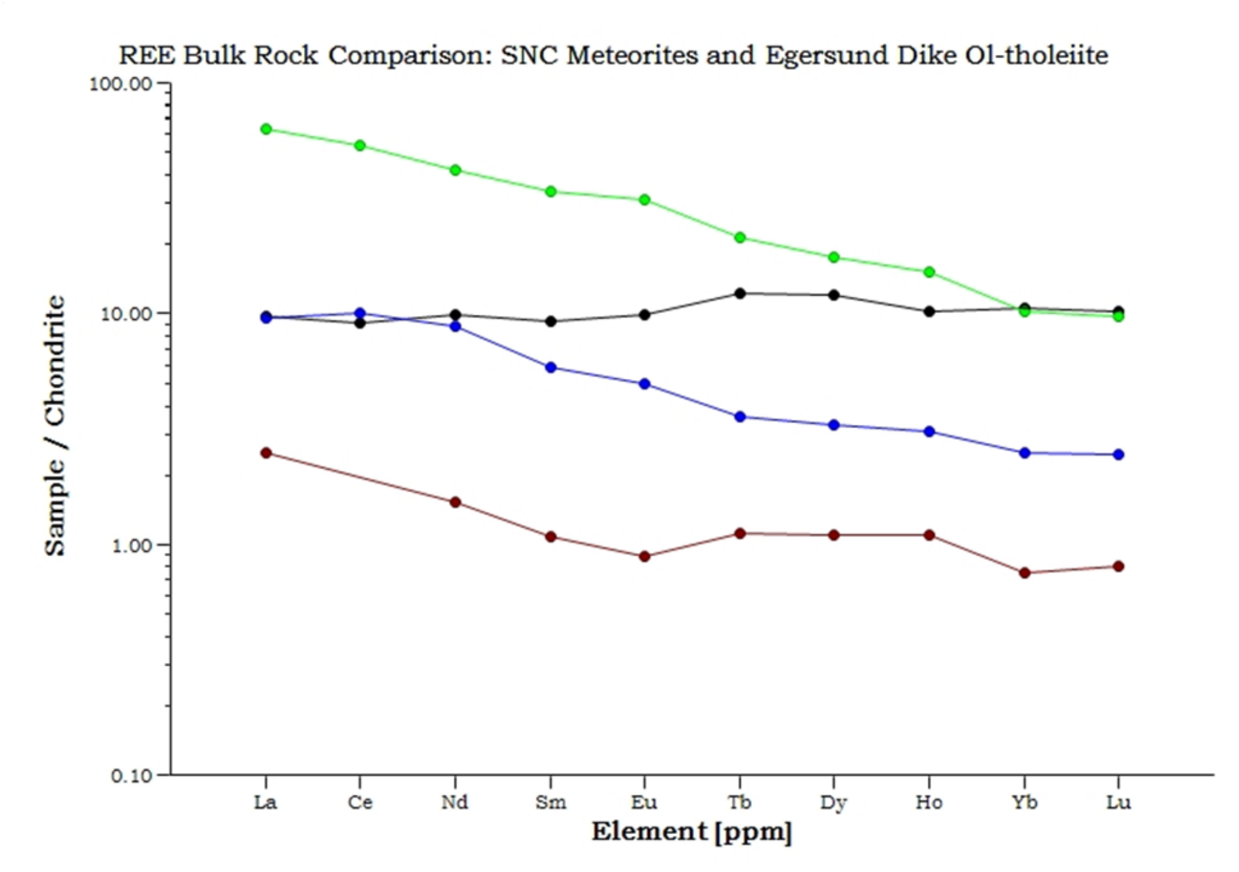


Figure 4.1 The average bulk rock rare earth elements were plotted for the Egersund Ol-tholeiites and the Martian rocks: Shergottite, Nakhla, and Chassigny. All were normalized to Chondrites. (Sources can be found in the appendix) Made in WinRock.

The average rare earth elements (REE) composition for Chassigny, Shergottite, Nakhla, and Egersund olivine tholeiites were normalized to chondrite REE based on the analyses performed done by McDonough & Sun 1995. The Egersund dike samples are much more enriched in light earth elements than any of the Martian meteorite samples. Light rare earth enrichment can be indicative of deviation from an enriched mantle source, which is consistent with the formation history of the Egersund dikes. Chassigny, on the other hand, is much more depleted. For most of the REEs plotted, Chassigny shows values very close to 1 indicating little enrichment compared to primal meteoritic material. Both Nakhla and Shergotty are basalts and fall between the REE composition of Chassigny and the Egersund Dike, but as Figure 4.1 shows, they are still highly depleted. This indicates that the SNC's REE composition is similar to that of the chondrites, the most primitive rock in the solar system, rather than the terrestrial olivine tholeiitic basalts derived from plume sources in the mantle. Differences in REE enrichment could therefore be indicative of differences in the compositions of the mantles of Earth and Mars.

Kaersutite Chemistry

The chemical formula units were calculated and plotted to reveal chemical differences and similarities among the kaersutite found on Mars, in the olivine tholeiitic Egersund dikes, and kaersutite found in other terrestrial settings—primarily alkaline basalts and mantle xenoliths. The Egersund dikes contain a rare variety of kaersutite that is anomalously silica-poor, alumina-rich, and alkali-poor (figures 5.1-5.4). The average terrestrial kaersutite has lower aluminum content, a high magnesium number, and is enriched in alkalis. Although fewer Martian samples were plotted for comparison, they appeared to have the largest range of compositions. Chemically, Chassigny Kaersutite is most consistent with the terrestrial kaersutites (figures 5.1-5.6). Chassigny kaersutites rarely plot outside the terrestrial kaersutite range. On average, the Martian samples are characterized by being very titanium-rich and alkali-poor when compared with terrestrial kaersutites. All Martian samples have aluminum contents consistent with average terrestrial kaersutite. The Martian kaersutite is chemically more similar to terrestrial kaersutite formed in alkaline basalts than to the Egersund dikes.

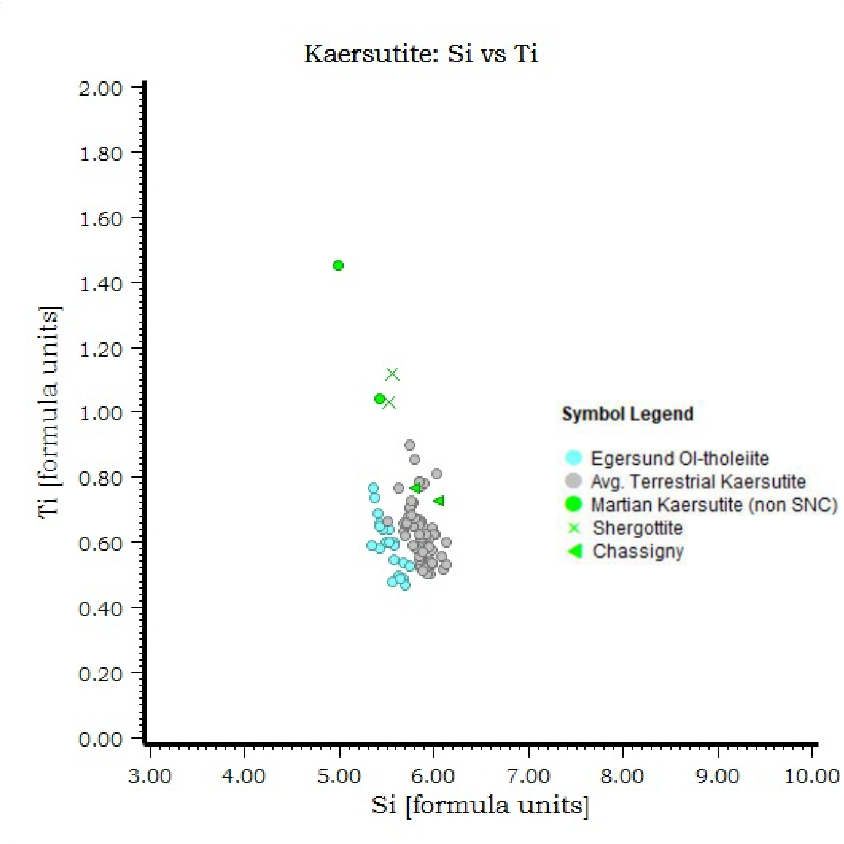


Figure 5.1 Silica vs titanium for Egersund samples, average kaersutite and Martian kaersutite.

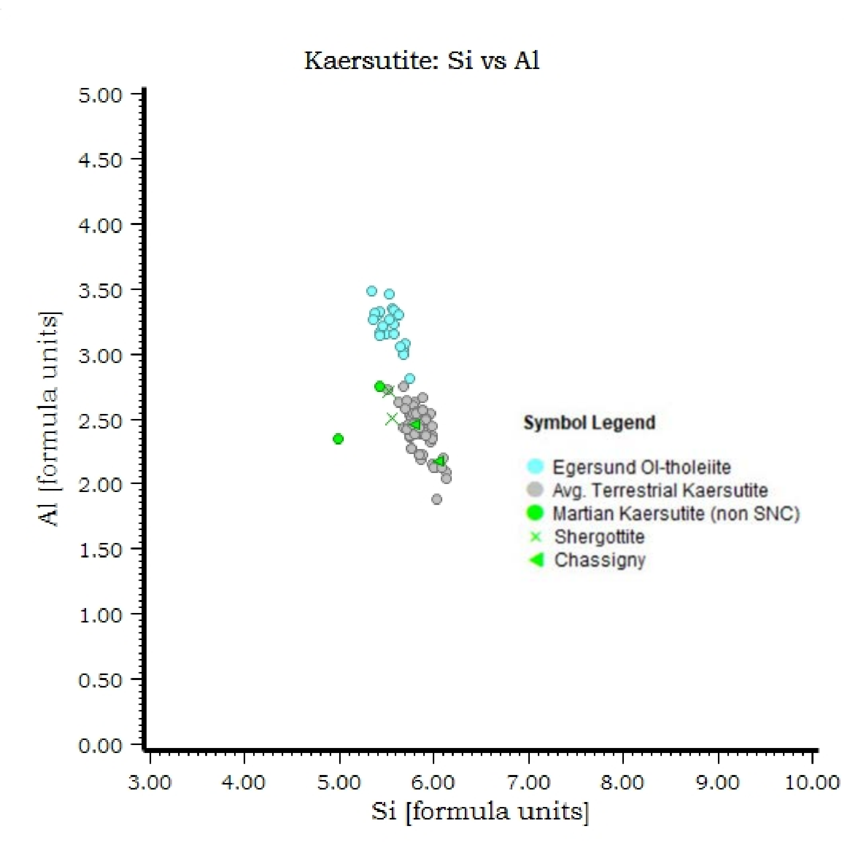


Figure 5.2 Silica vs aluminum for Egersund samples, average kaersutite and Martian kaersutite

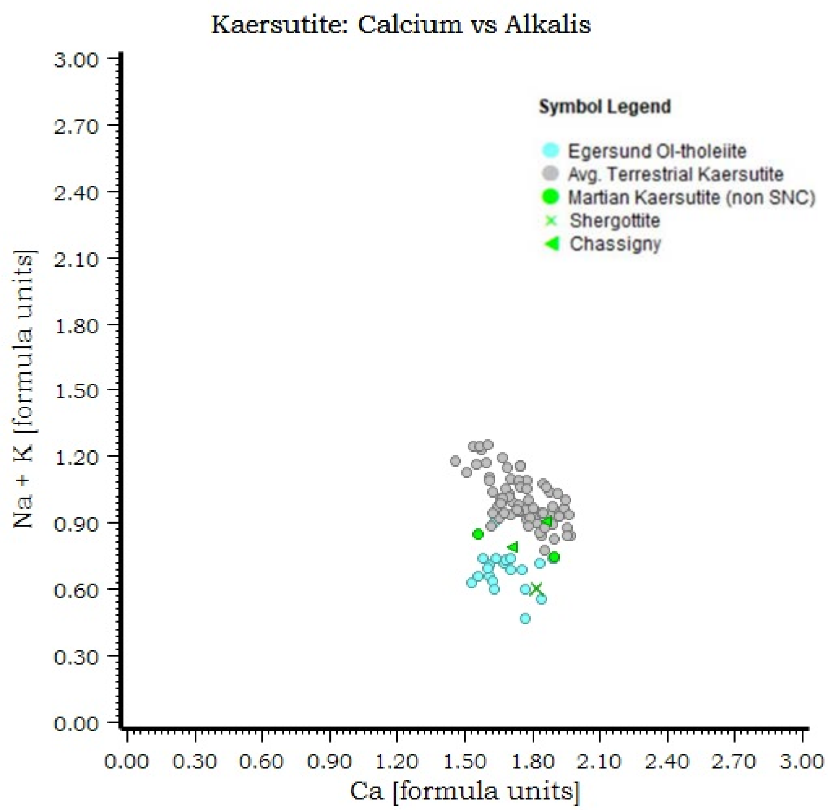


Figure 5.3 Calcium vs alkalis for Egersund samples, average kaersutite and Martian kaersutite.

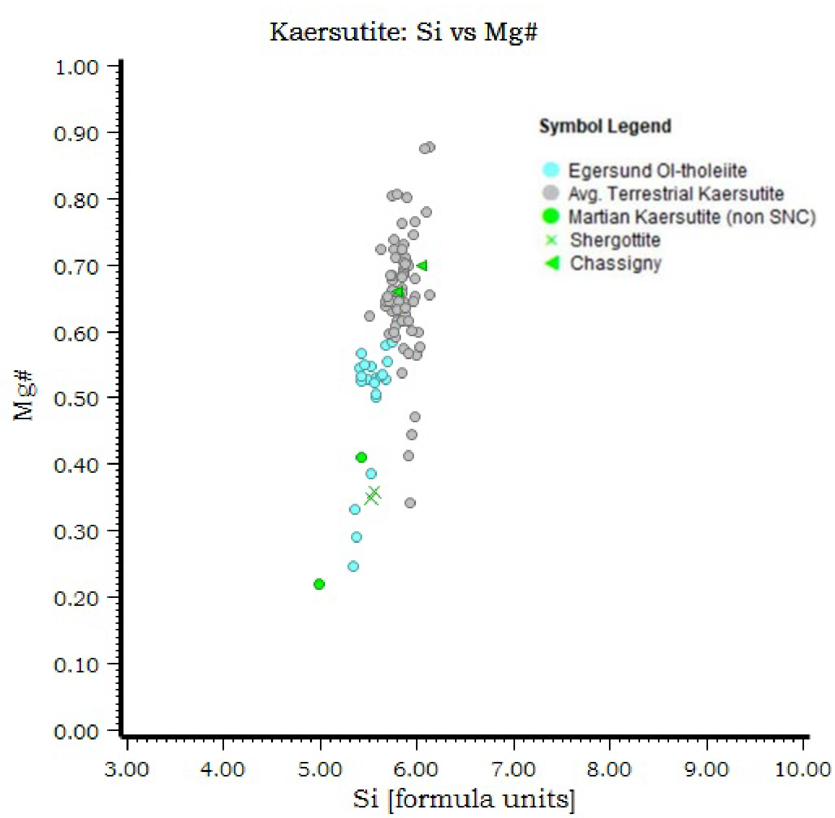


Figure 5.4 Silica vs Magnesium # for Egersund samples, average kaersutite and Martian kaersutite.

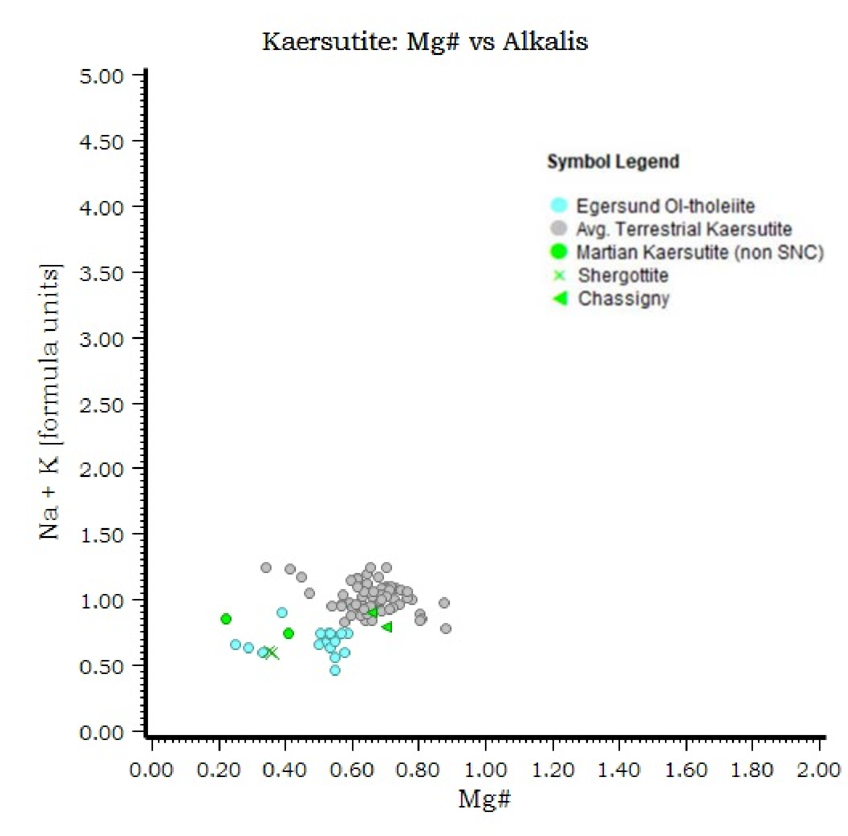


Figure 5.5 Magnesium # vs. alkalis for Egersund samples, average kaersutite and Martian kaersutite.

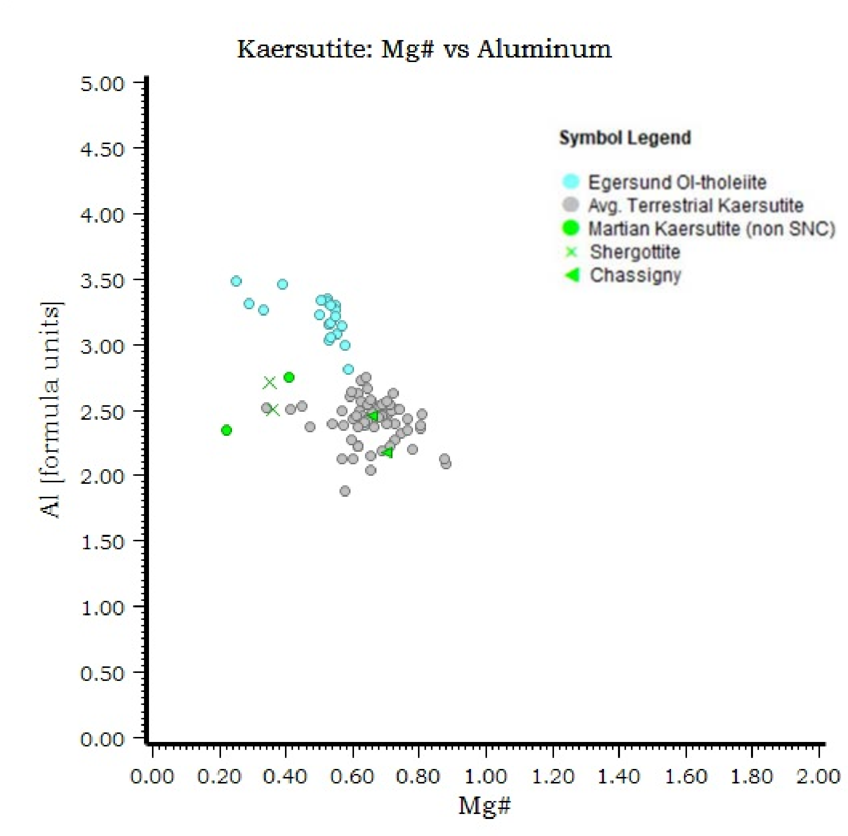


Figure 5.6 Magnesium # vs Aluminum for Egersund samples, average kaersutite and Martian kaersutite.

DISCUSSION

Kaersutite occurs in olivine grains in both the Egersund dikes and the Chassigny meteorite. However, the petrology of each rock reveals distinct differences, notably the zonation of the melt inclusions host mineral in the Egersund dikes and Shergottites and the lack of zonation in Chassigny olivines. Chassigny contains intact, homogenous olivine grains that appear to be in equilibrium with the rest of the melt, so it is possible that the kaersutite melt-inclusions are representative of the melt that crystallized the entire meteorite. Kaersutite is not found elsewhere in the meteorite probably because the original melt has been altered by its interaction with olivine. The interaction allowed kaersutite to crystallize only in the olivine melt inclusion and nowhere else in the meteorite (Johnson, 1991). An extensive study by Johnson et al. (1991) postulated that the original melt that formed Chassigny was an FeO-rich Al_2O_3-poor basalt. The chemical bulk rock composition of Chassigny does suggest a genetic link with processes that form tholeiitic magmas on earth. It must be noted that the SNC meteorites represent an incomplete picture of Martian magmatism based on the limited number of examples that are known to exist. Chassigny is a cumulate and may be representative of the cumulus pile either in an emplaced sill or within a thick flow sequence. The Rare Earth Elements are not strongly enriched and the occurrence of unzoned magnesium-rich, silica-poor, olivine with primary melt inclusions that show little reaction suggests cumulate pile was sequestered from the evolving melt. According to Bonin et al. (1998), the typical emplacement of a primary melt in the calc-alkaline rock sequence would include olivine + clinopyroxene+ pigeonite + plagioclase with volatile and titanium enrichment in the remaining melt. There are no known Martian meteorite examples with this mineralogy suggesting that either these rocks is not yet represented in the limited number of samples available, or that other differentiation processes occurred.

Olivines with kaersutite melt inclusions present in the Egersund dikes exhibit textures such as skeletal, strained, resorbed, reverse-zoned, and intergrown with plagioclase. Textures indicate that they are not in equilibrium with the melt that formed the olivine tholeiitic dike. Olivine grains with kaersutite inclusions are interpreted as xenocrysts. Kaersutite is not found outside of olivine inclusions, and it appears that the melt inclusion composition differs from the melt that crystallized the rest of the rock. The fact that kaersutite is highly unlikely to crystallize from a tholeiitic magma supports this notion. The mode of occurrence in the Egersund dikes appears to be similar to that in the pigeonite grains in the Shergottites. Pigeonite grains present in basaltic Shergottites are zoned and strained, indicating they are not in equilibrium with rest of the meteorite. Melt inclusions occur in the homogenous core of the crystals. The cores could have crystallized trapping its host melt inside. Then, after mixing with another magma the rim of the pigeonite could have further crystallized. Further evidence is that pigeonite and augite occur in approximately equal modal abundances, yet pigeonite shows more extensive zoning than augite, and kaersutite melt inclusions only occur in pigeonite. Another hypothesis for the formation of melt inclusions in Shergottites presented by Pitman and Treimann (2004) postulates that mixing did not occur but instead inclusions in pigeonite could have been trapped while the melt was still hydrous while inclusions in augite were trapped later on after water-loss. They argue that magma included in pigeonite would have grown to be calcium, titanium and aluminum rich which would result in the crystallization of kaersutite.

Presence of Shock

Another striking difference between the petrology of the Egersund dike olivine tholeiites and the Martian meteorites is the presence of shock features and alteration in the SNC's. Shergottite is the more heavily shocked than Chassigny, and most of the melt inclusions are irregular shaped, surrounded by radiation cracks, and include maskelynite. These features could support the alternative hypothesis that kaersutite formed via shock rather than crystallization at depth in the basaltic Shergottites. An experimental study by Monkawa (2003) was able to produce a melt from a starting material composed of a mixture of the minerals: augite, albite, ilmenite and Ti-magnetite. The melt that was produced contained between 6-12 wt% TiO_2 which is consistent with the Ti-rich nature of the Martian kaersutite (see appendix). However, the AlO_2 content of the melt was 7–8% whereas that of Martian kaersutites is 13-18 wt% (see appendix). Moreover, there were textural differences between experimental results and the Shergottite samples. It is possible that kaersutite in the Shergottite meteorites and in the Egersund dikes both formed via mixing, yet there remain many uncertainties. The sample size of the Shergottites is small and scientists have yet to perform petrologic analysis a Martian rock that is not shocked.

Geochemistry

The bulk rock chemistry of the Shergottites suggest Mars and Earth share a similar differentiation history. Shergottites are generally more enriched in REEs than either Chassigny or Nakhlites but are less enriched than the Egersund Dikes. The REE enrichment, presence of xenocrysts of olivine (poikilitic and zoned) and pyroxene containing melt inclusions suggest further differentiation. McCubbin et al. (2013) presented evidence that Shergottites may represent the eruptive end-member of Martian mantle melting. Textural evidence of oriented pyroxene crystals provides some indication of flow. The occurrence of kaersutite in melt inclusions in pyroxene would be inconsistent with shallow depth of formation in the Martian crust and would be evidence that these melt inclusions were not represented in the final melt forming the Shergottite. The bi-lithic Shergottite and the inferred two-stage magmatic evolution support a complex formation and differentiation history. The zonation in the pigeonite in the Shergottites show magnesium rich cores to iron-rich rims, also indicating tholeiitic enrichment which is consistent with the Ol-tholeiitic Egersund dikes.

CONCLUSIONS

- Petrologic examinations of both the Egersund dike and Shergottite phenocrysts containing kaersutite melt inclusion suggest that neither phenocryst is in equilibrium with the rest of the melt. This supports the idea that the host phenocrysts are actually xenocrysts, and that the melt that crystallized the kaersutite is not the same melt that crystallized either bulk rock.

- The Martian meteorites have been strongly shocked from the impact event that liberated them from Mars. The alteration that shock caused on the samples complicates analysis. Since there is yet to be a Martian sample return mission, and thus far no Martian rovers have analyzed rocks with kaersutite, it is not possible to rule out the formation of kaersutite by shock. In fact, experimental results reveal that a melt similar to the melt that crystallized kaersutite in the Shergottites can be formed via shock pressure. However, the experimental results yielded phenocryst textures that were very different than Shergottite.

- Geochemical data suggest that Mars and Earth share a similar differentiation history. Zonation of pigeonite phenocrysts toward an iron-rich composition indicates tholeiitic enrichment. This enrichment is consistent with the Ol-tholeiites in the Egersund dikes. Bi-lithic Shergottites and the suggested two-stage magmatic evolution support the idea that Mars has a complex formation and differentiation history.

Recommendations For Future Work

- It would be useful to make the same lithologic comparisons for bulk rock chemistry that were made for kaersutite chemistry. This would involve adding bulk rock chemistry data for rocks where the “average” terrestrial kaersutite is found (outside of the Egersund dikes). This would allow for a more complete comparison of kaersutite formation conditions.

- Little is known about the crystallization of kaersutite. An experimental study is needed to determine if it is possible for kaersutite to crystallize out of a tholeiitic (or oxidizing) melt.

- Once there is a sample return mission from Mars a comparison of non-shocked Martian tholeiitic basalt and lherzolite should be compared to Shergottite meteorites to determine the role that shock had in altering the mineralogy of the meteorites.

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APPENDIX A

Sample #	Rock Name	SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	FeO/ MgO	Na2O + K2O
Best,1974	Avg. Terrestrial Kaersutite	38.50	5.80	14.80	0.00	12.20	0.10	11.00	9.60	2.80	1.80	1.11	4.60
Best,1974	Avg. Terrestrial Kaersutite	40.40	4.70	14.70	0.10	10.20	0.10	13.60	10.40	2.70	1.50	0.75	4.20
Vinx and Jung	Avg. Terrestrial Kaersutite	40.11	4.82	14.56		9.18		13.92	11.17	2.39	2.20	0.66	4.59
Vinx and Jung	Avg. Terrestrial Kaersutite	41.38	4.67	13.70		9.08		14.96	11.38	2.61	1.92	0.61	4.53
Vinx and Jung	Avg. Terrestrial Kaersutite	40.23	4.92	14.21		10.19		13.36	10.83	2.51	2.05	0.76	4.56
Vinx and Jung	Avg. Terrestrial Kaersutite	39.82	4.99	14.26		10.39		13.28	11.02	2.47	2.04	0.78	4.51
Vinx and Jung	Avg. Terrestrial Kaersutite	40.28	4.85	14.53		9.84		13.78	11.42	2.47	2.16	0.71	4.63
Vinx and Jung	Avg. Terrestrial Kaersutite	39.81	4.76	14.58		10.52		13.08	11.01	2.46	2.09	0.80	4.55
Kesson	Avg. Terrestrial Kaersutite	38.85	6.02	14.83		13.25	0.18	10.72	10.29	2.71	1.03	1.24	3.74
Kesson	Avg. Terrestrial Kaersutite	38.67	5.71	13.31		13.40	0.15	10.15	11.56	2.20	2.03	1.32	4.23
Kesson	Avg. Terrestrial Kaersutite	38.20	6.23	13.81		11.75	0.17	11.29	12.13	2.46	0.85	1.04	3.31
Kesson	Avg. Terrestrial Kaersutite	38.67	5.90	13.50		14.49	0.19	9.50	11.88	2.55	1.05	1.53	3.60
Kesson	Avg. Terrestrial Kaersutite	37.40	6.00	15.70		12.26	0.20	11.40	11.90	2.30	1.50	1.08	3.80
Kesson	Avg. Terrestrial Kaersutite	39.51	5.64	14.26		12.49	0.09	11.36	10.12	2.80	1.59	1.10	4.39
wilkinson 1991	Avg. Terrestrial Kaersutite	39.50	5.24	15.20		11.40	0.15	11.50	9.46	2.82	1.64	0.99	4.46
frey 1978	Avg. Terrestrial Kaersutite	43.20	4.90	13.20		7.90	0.08	15.80	11.30	3.10	0.84	0.50	3.94
frey 1978	Avg. Terrestrial Kaersutite	40.00	5.00	14.60		11.70	0.16	13.00	10.60	2.80	1.19	0.90	3.99
frey 1978	Avg. Terrestrial Kaersutite	38.40	5.73	15.80		11.67	0.16	11.50	11.60	2.15	1.21	1.01	3.36
frey 1978	Avg. Terrestrial Kaersutite	39.40	5.94	13.60		12.46	0.14	11.60	10.90	2.32	1.65	1.07	3.97
wilkinson, 1961	Avg. Terrestrial Kaersutite	39.78	7.00	14.13		11.46	0.12	11.01	10.75	2.57	1.58	1.04	4.15
wilkinson, 1961	Avg. Terrestrial Kaersutite	39.01	6.05	13.60		12.14	0.14	11.73	12.05	2.51	1.11	1.03	3.62
wilkinson, 1961	Avg. Terrestrial Kaersutite	39.68	7.12	12.81		12.43	0.12	11.22	11.06	3.37	1.04	1.11	4.41
Schiano, 1992	Avg. Terrestrial Kaersutite	40.25	8.40	14.01	0.32	6.18	0.11	14.28	12.35	2.70	0.82	0.43	3.52
Schiano 1994 Kerg. Xeon	Avg. Terrestrial Kaersutite	40.31	7.91	14.57	0.27	6.00	0.05	13.97	11.93	2.50	0.88	0.43	3.38
Schiano 1994 Kerg. Xeon	Avg. Terrestrial Kaersutite	41.09	7.25	14.12	0.28	5.95	0.16	13.59	12.82	2.49	0.85	0.44	3.34
Righter	Avg. Terrestrial Kaersutite	39.20	5.02	13.20	0.01	16.69	0.42	8.40	10.29	2.19	2.10	1.99	4.29
Righter	Avg. Terrestrial Kaersutite	39.30	6.11	14.70	0.02	10.80	0.28	12.70	11.14	2.53	1.26	0.85	3.79
Righter	Avg. Terrestrial Kaersutite	39.20	6.07	14.70	0.01	10.46	0.30	12.80	11.30	2.42	1.24	0.82	3.66
baxter	Avg. Terrestrial Kaersutite	40.39	5.80	12.35		11.86	0.16	12.45	11.45	2.60	0.83	0.95	3.43
baxter	Avg. Terrestrial Kaersutite	40.32	5.57	12.11		13.57	0.25	11.37	11.45	2.66	0.89	1.19	3.55
baxter	Avg. Terrestrial Kaersutite	39.85	5.52	11.99		14.95		10.92	10.95	2.77	0.81	1.37	3.58
baxter	Avg. Terrestrial Kaersutite	39.42	5.01	14.20		11.41		12.35	11.57	2.78	0.78	0.92	3.56
aoki jpet 1963	Avg. Terrestrial Kaersutite	40.27	7.23	10.70		14.09	0.24	10.73	11.85	2.40	0.69	1.31	3.09
aoki jpet 1963	Avg. Terrestrial Kaersutite	39.68	7.12	12.81		12.43	0.16	11.22	11.06	3.37	1.04	1.11	4.41
aoki jpet 1963	Avg. Terrestrial Kaersutite	39.68	5.91	14.82		11.55	0.16	12.28	10.54	2.52	1.13	0.94	3.65
aoki jpet 1963	Avg. Terrestrial Kaersutite	39.20	6.53	13.87		10.96	0.11	11.96	12.37	1.99	1.45	0.92	3.44
Kyle, Jpet,1981	Avg. Terrestrial Kaersutite	38.70	6.39	13.00	0.17	9.24	0.12	13.65	12.20	2.46	1.38	0.68	3.84
Kyle, Jpet,1981	Avg. Terrestrial Kaersutite	39.00	5.86	12.40		10.60	0.19	12.95	11.90	2.74	1.24	0.82	3.98
Kyle, Jpet,1981	Avg. Terrestrial Kaersutite	39.60	5.81	12.70		9.79	0.13	13.60	11.60	2.90	1.29	0.72	4.19
Kyle, Jpet,1981	Avg. Terrestrial Kaersutite	38.80	6.34	13.60		11.20	0.17	12.35	11.70	2.78	1.38	0.91	4.16

Table 2 Major element chemistry from terrestrial kaersutite (non-Egersund dikes). [Part 1] Data provided by Dr. Michael Barton (Ohio State

Sample #	Rock Name	SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	FeO/ MgO	Na2O + K2O
Gamble & Kyle jpet 1987	Avg. Terrestrial Kaersutite	39.64	5.93	13.83	0.16	9.14		13.47	11.28	2.92	0.9	0.68	3.82
Gamble & Kyle jpet 1987	Avg. Terrestrial Kaersutite	39.25	6.6	14.45	0	8.45		13.44	11.45	2.93	0.7	0.63	3.63
Gamble & Kyle jpet 1987	Avg. Terrestrial Kaersutite	38	6.88	15.03	0	8.83		12.91	11.65	2.6	1.05	0.68	3.65
Gamble & Kyle jpet 1987	Avg. Terrestrial Kaersutite	39.73	5.93	14.8	0.07	9.57	0.07	13.32	11.48	2.58	1.06	0.72	3.64
Dorais am min 1990	Avg. Terrestrial Kaersutite	37.7	5.83	13.74		11.84	0.19	12.15	12.18	2.44	1.19	0.97	3.63
Vannucci GCA 1995	Avg. Terrestrial Kaersutite	42.13	4.87	12.15	1.26	4.08	0.05	16.42	11.89	2.75	0.02	0.25	2.77
Vannucci GCA 1995	Avg. Terrestrial Kaersutite	41.9	5.12	12.42	1.35	4.03	0.06	15.79	12.15	3.38	0.15	0.26	3.53
Irving Gsa 1974 Newer basalts	Avg. Terrestrial Kaersutite	38.9	4.4	14		21.5	0.21	6.3	9.4	3.1	1.7	3.41	4.8
Irving Gsa 1974 Newer basalts	Avg. Terrestrial Kaersutite	39.5	5.4	14.29		17.7	0.13	7.96	9.02	2.64	2.12	2.22	4.76
Irving Gsa 1974 Newer basalts	Avg. Terrestrial Kaersutite	40.5	4.9	14.7		11.28	0.12	11.5	10.6	3.2	1.5	0.98	4.7
Irving Gsa 1974 Newer basalts	Avg. Terrestrial Kaersutite	39	4.6	14		19.2	0.18	7.6	9.7	3	1.8	2.53	4.8
Best CMP 1970 GrpII	Avg. Terrestrial Kaersutite	40	5.16	14.83		12.08		11.36	11.77	2.36	1.11	1.06	3.47
Best CMP 1970 GrpII	Avg. Terrestrial Kaersutite	40.32	5.3	14		13.34		11.32	10.81	2.71	0.87	1.18	3.58
Best CMP 1970 GrpII	Avg. Terrestrial Kaersutite	39.79	5.5	14.26		14.01		10.28	10.93	2.63	1.06	1.36	3.69
Wilshire epsl 1971	Avg. Terrestrial Kaersutite	40.3	5.6	14	0.1	10.3	0.1	13.7	10.9	2.7	1.4	0.75	4.1
Wilshire epsl 1971	Avg. Terrestrial Kaersutite	41.5	4.9	13.8	0.1	8.3	0.1	15.2	10.8	2.7	1.4	0.55	4.1
Wilshire epsl 1971	Avg. Terrestrial Kaersutite	40.4	5.4	14.4		11.3	0.2	13.6	10.7	2.6	1.4	0.83	4
Wass Kiama Xenos	Avg. Terrestrial Kaersutite	38.8	6.11	14.1		10.3		12.6	12.3	2.07	2.18	0.82	4.25
Ellis cmp 1976	Avg. Terrestrial Kaersutite	41	5.36	11.6	0.04	11.6	0.18	12.4	9.78	3.4	1.37	0.94	4.77
Wilshire 1988 usgs 1443	Avg. Terrestrial Kaersutite	38.5	5.9	15.1		13.8	0.26	11.4	10.2	2.1	1.5	1.21	3.6
Wilshire 1988 usgs 1443	Avg. Terrestrial Kaersutite	38.4	5.9	13.8		12.5	0.21	12.8	11.2	2.3	1.2	0.98	3.5
Wilshire 1988 usgs 1443	Avg. Terrestrial Kaersutite	39.9	5.3	14.8	0.01	12.5		12.7	10.4	2.7	0.99	0.98	3.69
Wilshire 1988 usgs 1443	Avg. Terrestrial Kaersutite	38	5.5	14.6		12		12.7	10.4	2.7	0.85	0.94	3.55
Wilshire 1988 usgs 1443	Avg. Terrestrial Kaersutite	39	5.3	14.1		13.7		12	10.9	2.5	1.3	1.14	3.8
Deer.., Chain Silicates	Avg. Terrestrial Kaersutite	39.01	6.05	13.6		12.14	0.14	11.73	12.05	2.51	1.11	1.03	3.62
Deer.., Chain Silicates	Avg. Terrestrial Kaersutite	39.68	7.12	12.81		12.43	0.16	11.22	11.06	3.37	1.04	1.11	4.41
Deer.., Chain Silicates	Avg. Terrestrial Kaersutite	38.3	6.06	12.87		14.14	0.12	11.79	10.47	3.11	1.3	1.20	4.41
Irving and Frey, 1984, GCA	Avg. Terrestrial Kaersutite	39.4	5.1	13.7	0	12.2	0.13	12	10.9	2.5	1.8	1.02	4.3
Irving and Frey, 1984, GCA	Avg. Terrestrial Kaersutite	39.7	5.6	13.5	0	12.96	0.18	11.7	10.1	2.8	1.51	1.11	4.31
Irving and Frey, 1984, GCA	Avg. Terrestrial Kaersutite	40.1	5.7	14.2	0.19	7.9	0.14	14.3	11.4	2.5	1.9	0.55	4.4
Irving and Frey, 1984, GCA	Avg. Terrestrial Kaersutite	41	4.9	14.2	0	10.66	0.11	12.7	10.2	3.1	1.6	0.84	4.7
Irving and Frey, 1984, GCA	Avg. Terrestrial Kaersutite	40.4	4.7	15	0	10.2	0.1	13.4	10.3	3	2.2	0.76	5.2

Table 3 Major element chemistry from terrestrial kaersutite (non-Egersund dikes). [Part 2] Data provided by Dr. Michael Barton (OSU)

Sample #	Rock Name	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	FeO/ MgO	$Na_2O + K_2O$
Mars gv1	Shergottite	31.09	12.06	12.44	0.3	26.16	0.3	4.25	9.08	2.53	0.27	6.16	2.8
Treiman,1985, Meteoritics	shergottite	35.95	9.65	13.77	0.25	18.25	0.36	5.71	10.97	1.89	0.13	3.20	2.02
Treiman,1985, Meteoritics	Shergottite	36.11	8.92	15.08	0.52	18.25	0.35	5.42	11.09	2	0.11	3.37	2.11
Treiman,1985, Meteoritics	Zagami (shergottite)	35.15	8.94	15.13	0.37	16.18	0.29	6.4	11.48	2.38	0.2	2.53	2.58
Johnson et al 1991, GCA	Chassigny	39.49	7	14.22	0	10.47	0.17	11.53	11.8	2.99	0.33	0.91	3.32
Floran,1978, GCA	Chassigny	41.6	6.7	12.7	0.68	9.8	0.21	12.6	11	2.64	0.27	0.78	2.91
grp2-1 sp3	Egersund Ol-tholeiite	36.96	5.4	18.01	0.02	14.69	0.21	9.22	11.53	2.35	0.19	1.59	2.54
grp2-1 sp4	Egersund Ol-tholeiite	38.37	4.43	17.38	0.01	14.57	0.23	9.16	11.91	2.49	0.17	1.59	2.66
grp2-1 sp12	Egersund Ol-tholeiite	38.55	4.88	17.27	0.02	13.55	0.19	10.44	11.24	2	0.17	1.30	2.17
grp2-1 sp15	Egersund Ol-tholeiite	37.26	4.93	17.92	0	15.1	0.26	9.55	10.05	2.35	0.17	1.58	2.52
grp3 sp3	Egersund Ol-tholeiite	37.53	5.34	18.45	0	15.4	0.2	8.65	10.11	2.04	0.39	1.78	2.43
grp3 sp1	Egersund Ol-tholeiite	38.66	4.23	17.75	0.03	14.38	0.17	10.08	10.61	2.38	0.21	1.43	2.59
grp3 sp6	Egersund Ol-tholeiite	36.63	6.21	18.96	0	13.64	0.19	9.2	11.64	1.81	0.20	1.48	2.01
grp3 sp9	Egersund Ol-tholeiite	37.35	4.34	19.12	0	15.06	0.26	9.32	10.07	2.23	0.32	1.62	2.55
grp3 sp10	Egersund Ol-tholeiite	37.44	5.72	18.79	0	13.59	0.24	9.21	11.18	1.55	0.14	1.48	1.69
grp3 sp12	Egersund Ol-tholeiite	36.81	5.27	19.06	0.04	14.83	0.17	9.22	11.05	2.31	0.18	1.61	2.49
grp3 sp11	Egersund Ol-tholeiite	37.97	5.36	19.34	0	14.56	0.27	8.34	10.43	2.2	0.62	1.75	2.82
grp3 sp13	Egersund Ol-tholeiite	36.32	5.84	17.99	0.01	15.3	0.24	9.85	10.09	2.06	0.20	1.55	2.26
grp3 sp14	Egersund Ol-tholeiite	38.27	4.52	19.06	0.02	14.26	0.24	9.12	10.67	2.41	0.23	1.56	2.64
grp3 sp16	Egersund Ol-tholeiite	37.1	5.81	18.56	0	14.45	0.22	9.89	10.81	2.28	0.19	1.46	2.47
grp4 sp1	Egersund Ol-tholeiite	39.21	4.85	16.3	0.04	13.87	0.2	10.99	10.85	2.46	0.20	1.26	2.66
grp1 sp11	Egersund Ol-tholeiite	35.21	6.46	18.39	0	21.8	0.39	5.01	9.36	2.03	0.18	4.35	2.21
grp1 sp14	Egersund Ol-tholeiite	34.77	5.13	19.29	0.03	23.15	0.37	4.28	9.5	2.05	0.25	5.41	2.3
grp1 sp19	Egersund Ol-tholeiite	35.06	6.7	18.2	0.01	20.38	0.29	5.72	9.95	1.91	0.15	3.56	2.06
sp7	Egersund Ol-tholeiite	37.98	6.01	18.63	0	15.02	0.21	11.03	10.31	2.24	0.64	1.36	2.88
spa8	Egersund Ol-tholeiite	37.48	5.41	19.96	0	17.2	0.25	6.13	10.32	2.16	1.49	2.81	3.65

Table 4 Martian and Egersund dike kaersutite major element chemistry. Data provided by Michael Barton (OSU)

APPENDIX B

Sample #	Rock Name	SiO2	Al2O3	TiO2	FeO	MnO	CaO	MgO	K2O	Na2O	P2O3	FeO/MgO	Na2O + K2O
118C	Egersund Ol-tholeiite	48.51	16.87	1.81	11.64	0.13	10.20	7.52	0.57	2.44	0.30	1.55	3.01
108	Egersund Ol-tholeiite	48.59	16.86	2.05	10.81	0.16	10.36	7.72	0.52	2.67	0.25	1.40	3.19
121	Egersund Ol-tholeiite	48.55	17.96	1.64	9.55	0.10	11.00	7.45	0.92	2.57	0.26	1.28	3.49
122	Egersund Ol-tholeiite	49.15	18.09	1.68	9.43	0.08	10.98	7.40	0.43	2.48	0.27	1.27	2.91
118	Egersund Ol-tholeiite	48.69	18.31	1.56	9.38	0.07	10.90	7.65	0.48	2.69	0.28	1.23	3.17
184	Egersund Ol-tholeiite	47.86	16.72	1.83	11.11	0.17	9.18	9.39	0.76	2.69	0.27	1.18	3.45
H12 Chill	Egersund Ol-tholeiite	49.27	16.39	1.80	10.28	0.18	9.28	8.67	1.01	2.80	0.32	1.19	3.81
186	Egersund Ol-tholeiite	48.07	17.25	1.77	10.67	0.16	9.17	9.32	0.73	2.58	0.27	1.14	3.31
H12 Core	Egersund Ol-tholeiite	49.07	17.14	1.67	9.65	0.17	9.71	8.51	0.94	2.83	0.31	1.13	3.77
185	Egersund Ol-tholeiite	48.00	17.43	1.71	10.50	0.16	9.08	9.54	0.63	2.67	0.27	1.10	3.30
142	Egersund Ol-tholeiite	48.83	17.98	1.49	9.65	0.16	9.61	9.11	0.43	2.49	0.25	1.06	2.92
141	Egersund Ol-tholeiite	48.62	17.21	1.56	9.99	0.17	9.63	9.55	0.48	2.54	0.24	1.05	3.02
Shergotty	Shergottite	51.36	7.06	0.87	19.41	0.53	10.00	9.28	0.16	1.29	0.80	2.09	1.45
Nakhla	Nakhla	48.24	1.45	0.29	20.64	0.54	15.08	12.47	0.10	0.42	0.12	1.66	0.52
Chassigny	Chassigny	38.16	0.69	0.10	27.10	0.53	0.60	31.60	0.04	0.13	0.06	0.86	0.17

Table 5 SNC meteorite and Egersund dike (samples with kaersutite melt inclusion only) bulk rock major element chemistry. Data provided by Michael Barton (OSU)

Appendix C

REE	Shergottite	Nakhla	Chassigny	114C	108	121	122	11b	H12Chill	H12 Core
La	2.29	2.28	0.59	14.76	13.59	28.09	14	12.66	20.54	20.31
Ce	5.54	6.2	-	33.71	28.26	53.99	31.4	27.36	39.86	40.04
Nd	4.50	4.06	0.7	32.41	-	28.23	34.61	31	-	-
Sm	1.37	0.86	0.16	4.454	4.49	7.21	4.227	3.7	6.02	6.02
Eu	0.56	0.28	0.05	1.87	1.419	2.189	1.567	1.739	1.929	1.849
Tb	0.44	0.13	0.04	1.15	1.052	1.42	0.631	1.01	1.38	1.19
Dy	2.94	0.81	0.27	-	-	-	-	-	-	-
Ho	0.56	0.17	0.06	-	-	-	-	-	-	-
Tm	0.38	-	-	-	-	-	-	-	-	-
Yb	1.69	0.4	0.12	1.88	1.595	2.415	1.59	1.58	1.49	1.58
Lu	0.25	0.06	0.02	0.3	0.24	0.45	0.31	0.23	0.44	0.46
Hf	1.97	0.29	-	3.56	3	4.47	3.18	2.87	3.84	8.59

Table 6 SNC and Egersund dike (samples containing kaersutite) bulk rock rare earth element (REE) data. Data provided by Michael Barton (OSU)